Research in Economics 71 (2017) 225–235

Contents lists available at ScienceDirect

Research in Economics

journal homepage: www.elsevier.com/locate/rie

The private and social consequences of purchasing an electric vehicle and solar panels: Evidence from California☆

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ARTICLE INFO

Article history:
Received 3 November 2016
Accepted 2 December 2016
Available online 15 December 2016

Keywords:
Renewable energy
Greenhouse gas
Electric vehicles
Solar panels

ABSTRACT

Rising greenhouse gas emissions raise the risk of severe climate change. The household sector′s greenhouse gas emissions have increased over time as more people drive gasoline cars and consume electricity generated using coal and natural gas. The household sector′s emissions would decline if more households drove electric vehicles and owned solar panels. In recent years automobile manufacturers have been producing high-performance electric vehicles, and solar panels are becoming more efficient and less expensive. Using several data sets from California, we document evidence of the growth of the joint purchase of electric and hybrid vehicles and solar panels. We discuss pricing and quality trends for these green durable goods.

1. Introduction

All over the world, more households are living at low density in the suburbs of metropolitan areas. Improvements in road networks, rising incomes and the demand for newer, larger homes have fueled this trend (Margo, 1992; Glaeser and Kahn, 2004; Baum-Snow, 2007; Baum-Snow et al., 2012). Such suburbanization offers private benefits but imposes social costs. In the absence of a national carbon tax, decentralized living can significantly contribute to greenhouse gas emissions through a reliance on gasoline fired cars and ample use of electricity for large suburban homes with the electricity generated by fossil fuels (Jones and Kammen, 2014; Graff Zivin et al., 2014). The transportation and residential and commercial sectors are responsible for 38% of U.S greenhouse gas emissions.[1]

Suburban household carbon emissions would decline if they install solar panels and buy an electric vehicle that charges at home.[2] If such households reduce their carbon emissions, then they would be less likely to oppose carbon pricing. In the United States today, there are significant political divisions with respect to support for public policies to mitigate

☆ We thank Matthew Shepherd for excellent research assistance. We thank the UCLA Ziman Center for Real Estate and the UCLA Transdisciplinary Seed Grant for generous funding.

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[1] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

[2] See Borenstein and Bushnell (2015) for a discussion of issues associated with the growth in intermittent renewable generation sources such as solar PV systems.

http://dx.doi.org/10.1016/j.rie.2016.12.002
1090-9443/

climate change. Democrats who tend to be highly educated and cluster in center cities tend to support such policies while Republican suburbanites tend to oppose such policies. President-Elect Donald Trump is likely to overturn the promises that President Obama's negotiators made at the COP 21 Paris greenhouse gas treaty conference. His political view is consistent with academic findings that have examined the political economy of support for carbon mitigation policy. This research has documented that Congressional Districts that are poorer, featuring more conservative representatives and with a larger per-capita carbon footprint tend to oppose climate mitigation policy (Cragg et al., 2013). Even in California, suburban voters have opposed carbon cap and trade programs (Holian and Kahn, 2015).

One political economy explanation for suburban opposition to carbon pricing is that this group is aware that it will bear more of the incidence of a carbon tax than center city residents. The diffusion of solar panels and EV vehicles could increase political support for carbon pricing because the costs of this policy to suburbanites would decline.

This paper studies Californian demand for solar panels and electric and hybrid vehicles. We use individual-level data on electric vehicle sales in California to explore the stated motivations for purchasing a particular vehicle and investigate the factors that determine which vehicle is chosen. Our results are consistent with hypothesis that consumers view solar panels and electric vehicles as complements and they are increasingly investing in both durable goods. We document these facts using two geocoded rebate data sets. In addition to presenting new empirical results, we also provide details about the evolving quality of these green goods.

2. Consumer demand for electric vehicles and solar panels

Differentiated consumer products such as cars represent bundles of packaged attributes. In the hedonic pricing equilibrium, heterogeneous consumers will select their favorite bundle as they face the non-linear attribute pricing function (Rosen, 1974). Most consumers are unlikely to recognize that differentiated products differ with respect to their social externality consequences. For example, a household seeking a safe vehicle may choose a large mini-van and will recognize that such a vehicle consumes more gallons of gasoline (a private cost) while ignoring the social costs associated with such fuel consumption (i.e. this vehicle creates more greenhouse gas emissions per mile of driving) (Anderson and Auffhammer, 2014; Petrin, 2002).

A consumer's vehicle choice problem follows closely the hedonic framework in Rosen (1974). Each vehicle has a quality index Z that is composed of an index g that measures the vehicle's environmental performance ("greenness"), and an index q measuring the vehicles performance (aesthetics, horsepower, etc.). Households differ in their level of income and preferences for g and q. High-quality vehicles are more expensive than low-quality vehicles which is reflected in a convex price function P(Z). Households with higher incomes or stronger preferences for vehicle performance will choose a high performing vehicle (such as the Tesla), while other households will choose a vehicle with a lower performance rating (such as the Nissan LEAF).

Among electric vehicles, the Tesla stands out for its quality. With the introduction of the Tesla Roadster in 2008, Tesla became the first manufacturer to produce an all-electric vehicle that was available for sale in the United States. The Tesla Roadster's all-electric range of over 200 miles is only bested by the current Tesla Model S that was introduced in 2012. The Model S was the first luxury all-electric vehicle to be introduced in the United States and proved that an all-electric vehicle can compete with the most popular luxury car brands. The Model S (version P100D) can achieve an all-electric range of up to 315 miles on a single charge and can accelerate from 0 to 60 MPH in 2.5 s. This impressive acceleration time competes with one of America's highest performance muscle cars – the Corvette Z06.[3]

Conditional on a household having purchased an electric vehicle, or anticipating that it will purchase an electric vehicle, how does this affect solar panel demand? Ignoring direct utility gained from engaging in conscious environmentalism and assuming there are no rebound effects, this household will compare its operating costs from its current lifestyle with and without solar panels. Assuming there is no lease payment for the solar system, households will compare the average price of electricity with solar (P^s) and the fixed cost of having solar panels installed (F) to the average price of electricity currently bought from a local utility (P^u). Assume also that the amount of electricity consumed (x_t) is the same with or without solar panels and that $P^s < P^u$.[4] If $F + \sum_{t=0}^{T} P_t^s x_t < \sum_{t=0}^{T} P_t^u x_t$, households will adopt solar panels. That is, if total expenditures on electricity generated by solar are less than the total expenditures without, the household will have a financial incentive to have solar panels installed. This inequality can be re-written as $F < \sum_{t=0}^{T} (P_t^u - P_t^s) x_t$.

This inequality indicates that households will be more likely to adopt solar panels based on financial incentives if: (1) innovative financing or competition reduces or eliminates the fixed cost (monetary and non-monetary) households must

[3] With respect to the all-electric range, the closest competitor to the Model S is the much smaller and less luxurious all-electric Kia Soul with a range of 93 miles. The Model S is also the largest car in its class meaning the performance benefits do not come at the expense of comfort. While this vehicle is expensive, we discuss below how the introduction of leasing and innovative financing schemes lowers the annual cost of operating the vehicle and thus opens the possibility for more people to purchase high-quality electric vehicles.

[4] For simplicity, we assume no discounting and that the price of electricity from solar or a utility are known with certainty.

pay to have solar panels installed, (2) if competition among solar panel manufacturers/installers creates a large difference between the price of electricity from solar panels relative to purchasing from the local utility, and (3) if there is a large increase x_t (for example, from the purchase of an EV) and the change in electricity consumption can be offset with installed solar capacity.[5]

Our discussion assumes that batteries exist so that a household who buys solar panels and an EV does not buy any electricity from the local electric utility. Recently, several manufactures have unveiled home battery systems that will store energy during the day that can be used to offset some or all of the electricity used though the night.[6] This increased storage will allow utilities to move away from fossil-fuel based generation to meet peak demand and instead meet this demand with power generated by renewable sources.

3. Declining prices for electric vehicles and solar panels

The quality-adjusted prices of high-quality solar panels and electric vehicles are declining over time. For example, between 2011 and 2016, the Chevrolet Volt has seen a drop in the manufacturer's suggested retail price from $41,000 to $33,170 for the base model, while increasing the engine size from 1.4 to 1.5 L. During this same time, the all-electric range as increased from 35 miles to 53 miles. The combined range (gasoline and the electric motor) has increased from 380 to 420 miles. When comparing vehicles that have an electric and conventional model, an interesting trend has also emerged. Between 2012 and 2015, the price of the Ford Focus Electric fell from $39,200 to $29,170 while the base model Ford Focus FWD 2.0 L 4-cylinder version increased from $16,500 to $17,170. These trends suggest that electric vehicles are in fact becoming less expensive relative to their conventional alternatives.[7] Data from California's Solar Statistics website shows that there has been a 13.5% decrease in the price per Watt of electricity generated. This technology continues to be more expensive than conventional energy sources but learning by doing and international trade and specialization offers the possibility of future further price declines (see Borenstein (2012), Sawhney and Kahn (2012), and Van Benthem et al. (2008)). If these trends continue, high-quality electric vehicles and solar panels will be accessible to households with more moderate incomes.

4. The greenhouse gas emissions implications of EVs and solar panel purchases

Recent research has documented that in several locations in the United States (such as Ohio) that electric vehicles can lead to more greenhouse gas emission than their conventional internal combustion engine alternative. Graff Zivin et al. (2014) show that charging and EV during the recommend hours at night leads to EVs generating more emissions per mile than a conventional internal combustion vehicle. Holland et al. (2015) also finds a significant amount of spatial variation in the benefits of driving electric vehicles in the United States. In the western United States and parts of Texas, driving an electric vehicle results in positive environmental benefits. However, in the 38 other states, the environmental benefits are negative (up to a cost of 3 cents per mile in Grand Forks, North Dakota). In these areas, electric vehicles may result in negative environmental benefits because: (1) the electricity used to charge the vehicles is from polluting fossil fuels, and (2) because the majority of local externalities from driving an electric vehicle are exported to other regions where the electricity is being generated.

These findings highlight that the environmental benefits of electric vehicles increase sharply if the power is generated by clean sources such as solar. Even in California a large percentage of power is generated using natural gas. Combing data from the National Renewable Energy Laboratory with housing estimates from the 2013 American Community Survey reveals that households in more than 50% US counties accounting for 48% of single detached housing units in the United States could offset at least 1000 kW h per month of electricity with 50 m^2 of solar panels.[8] This is more than enough to completely offset electricity consumption for the average household and cover the additional usage of and electric vehicle for many households. This means the benefits of a joint purchase of solar and an electric vehicle are not limited to areas like sunny southern California. The endogenous innovation literature predicts that this large potential market will likely trigger entry of new firms and products leading to more low-cost high-quality electric vehicles and solar systems (Acemoglu and Linn, 2004).

5. Data

We use several individual-level and aggregated datasets from California to study patterns in electric vehicle and solar panel purchases. These datasets are described in Table A1. The first dataset is a survey that was completed by 19,460 indi-

5 People who live in the center city are more likely to live in multi-family housing. In such housing, issues arise concerning who makes the decision over installing solar panels and investing in the garage's recharging stations. Such split-incentives problems hinder the joint adoption of solar panels and EVs. In single-family owner occupied housing, such incentive problems do not arise. For more on the split-incentives issue see Gillingham et al. (2012).

6 http://www.plugincars.com/quick-guide-buying-your-first-home-ev-charger-126875.html.

7 Data on vehicle prices and ranges come from the U.S. Department of Energy. Since the interior and exterior features do not significantly change over time, quality is measured by vehicle efficiency with respect to the miles per gallon equivalency.

8 We assumed that solar panels were capable of converting 15% of the sun's power into usable electricity.

Table 1
Summary statistics for census tract variables.

Variables	(1) Mean	(2) Std. Dev.	(3) Min	(4) Max
% Electric	0.165	0.507	0	12.74
% Hybrid	0.121	0.309	0	5.795
% Electric or hybrid	0.286	0.769	0	17.74
# Electric	2.814	9.465	0	322
# Hybrid	2.042	5.662	0	155
# Electric or hybrid	4.856	14.32	0	413
# Solar	25.10	42.10	0	823
% Solar	1.511	2.270	0	42.11
% Democrat, green, natural law, or peace and freedom	47.03	13.51	15.07	84.48
% Bachelor's degree or higher	30.25	20.43	0	95.20
Median income	66.58	32.16	4.607	245.9
% Black	5.942	9.335	0	90
% Hispanic	37.06	26.47	0	100
People per square mile	8555	9532	0.231	174,140
Miles to central business district	17.15	17.21	0.0251	162.9

Notes: This table contains summary statistics for each of the 7967 census tracts that are used in the analysis below. Vehicle and solar counts and percentages are census tract-year observations (7967 $\times$ 6 years = 47,802 observations). Data for each of the vehicle count/share variables are from rebate statistics provided by California's Clean Vehicle Rebate Project, and data for the percentage of households with solar are from California's Distributed Generation Statistics. Political ideology and voting outcomes data are from the University of California, Berkeley's Statewide Database, and the demographic data are from the 2014 American Community Survey 5-year estimates. A description of how the datasets were combined into census tracts can be found as a table note in Table A1.

Table 2
The most important factor in the electric vehicle purchase decision.

Response	BMW	Tesla	Total
Reducing environmental impacts	32.32	23.69	22.01
Vehicle performance	3.75	20.26	4.99
Saving money on fuel costs	22.72	13.12	36.9
HOV lane access	14.52	8.02	15.9
Increased energy independence	6.09	8.41	6.14
A desire for the newest technology	11.94	15.64	5.23
Supporting the diffusion of EV technology	3.75	6.10	4.52
No answer	.940	.88	.73
Other	3.98	3.89	3.57

Notes: This table summarizes the most important factor in the purchase decision for all 19,460 survey respondents that purchased a plug-in electric vehicle between September 2012 and May 2015. The values represent the percentage of survey respondents that indicated each category was the most important factor in their decision. The BMW column describes the responses of the 427 survey respondents that purchased a BMW, and the Tesla column describes the responses of the 3293 survey respondents that purchased a Tesla. The total column includes all 19,460 survey respondents.

viduals that applied for a rebate through California's Clean Vehicle Rebate Project (CVRP).[9] This program has offered rebates as large as $7000 for the purchase or lease of a new eligible zero emissions or plug in hybrid light duty vehicle. This dataset contains the manufacturer of the vehicle that was purchased, the respondent's primary decision factors that influenced the purchase decision, consumer demographics, and whether or not the applicant has, or plans to install, a solar PV system at their home.

In addition to the applicant-level survey data, we use another dataset provided through the CVRP that contains up-to-date information on every new-vehicle rebate in California. This dataset provides the application date, vehicle type, census tract, zip code, and electric utility for all 160,192 individuals that applied for a rebate through July 2016. We use these data to calculate the number of each vehicle type (all electric or hybrid) in each Census tract and zip code.[10]

Next, we use data from California's Distributed Generation Statistics website that describes the full set of all interconnected solar PV systems in the PG&E, SCE, and SDG&E utilities. The zip code for each system is provided and is used to calculate the total number of solar PV systems in each zip code. This zip code level data is then matched to census tracts using a crosswalk file provided by the United States Department of Housing and Urban development.

[9] The survey responses are for individuals that purchased an electric vehicle between September 12, 2012 and May 31, 2015. Once a household's application for a rebate has been approved by the Clean Vehicle Rebate Program, they are invited by email to participate in an online survey that asks about their buying experience, the vehicle they purchased, their demographics, and their motivations for purchasing the vehicle. An email reminder is sent to each household that has not completed the survey when they are notified that their rebate check is in the mail.

[10] We only count vehicles in the PG&E, SCE, and SDG&E utility areas since these are the only three utilities in the solar data set.

Table 3
EV owners stated plans for installing solar panels.

Do you have/plan to install a PV system?	BEV	Plug-in hybrid
Currently installed	22.5	17.27
Plan to install within one year	21.58	18.86
No and have no plans	54.84	62.82
No answer	1.08	1.05
Number of responses	11,749	7711

Notes: Buyers of a plug-in electric vehicle that responded to the survey were asked whether or not they had a PV system installed or if they had plans to install a PV system. The column "BEV" summarizes the responses of those that purchased an all-electric vehicle, and the "Plug-in Hybrid" column summarizes the responses of those that bought an electric/gas hybrid plug-in vehicle. Values indicate the share of households in each group that answered yes to each question.

We control for Census tract demographics using data from the 2014 American Community Survey's 5-year estimates. We control for the political ideology of each geographic area using voter registration data from the University of California Berkeley's Statewide Database. This database contains the number of registered voters in each political party in 2010 for each census block in.[11] Summary statistics for the variables used are shown in Table 1. A description of how the datasets were merged using different geographies is included in the appendix.

6. Hypothesis testing

First, we posit that owners of the highest quality electric and hybrid vehicles will differ from the owners of other brands with respect to their motivations for purchasing their vehicle and that those currently buying the high-quality electric and hybrid vehicles will have higher incomes and be more educated. Specifically, these buyers will be much more likely to care about vehicle quality and performance than those that purchase other makes. Second, many households that purchase a plug-in electric vehicle will also invest in solar panels. Since households that purchase both can take advantage of lower operating costs compared to one or the other, we expect to find evidence of a complementarity between these two durable goods. Furthermore, households that purchase an all-electric vehicle will be more likely to purchase solar panels when compared to households that purchase a plug-in hybrid.

6.1. Stated attitudes

We use the applicant-level survey to investigate the stated motivations for vehicle purchases. The sample consists of 19,460 rebate applicants that completed the survey questions about their purchasing decision and experience. Results from this survey are presented in Table 2. Owners of high-quality electric and hybrid vehicles (BMW and Tesla) cite a concern for the environment slightly more often than the average respondent does but they are much less concerned about fuel savings. Interestingly, Tesla owners are much more concerned with vehicle performance while BMW owners are less concerned with vehicle performance.[12] Buyers of a BMW or Tesla were approximately two and three times more likely to be motivated by owning the latest in electric vehicle technology, respectively. These results show that there are two types of consumers that will purchase the Tesla and potentially other high-performance EVs. The first is an environmentalist with a taste for high quality and high performance durable goods. These consumers support the environment but always want the highest quality and best performing vehicle. The second type of consumer is one that values quality and performance while viewing environmental benefits as secondary.

Since buyers of an all-electric vehicle can offset some, if not all, of the additional electricity that is used to charge their vehicle by installing solar panels, we posit that these buyers should be more likely to bundle their vehicle purchase with solar panels. We test this hypothesis using data from the survey of plug-in electric vehicle buyers and the results are summarized in Table 3. Of the 11,749 survey respondents that purchased an all-electric vehicle, 44% stated they either have solar panels installed or plan to have them installed within one year. Of the 7711 buyers of a plug-in hybrid, only 36% stated that they have installed solar panels or plan to install solar panels within one year. This result is consistent with the hypothesis that consumers are aware of the benefits of a joint purchase of both solar PV systems and electric vehicles.

[11] If passed, this proposition would have suspended the implementation of California's Global Warming Solutions Act of 2006 until California's unemployment rate dropped to 5.5% or below for four consecutive quarters.

[12] This could be because BMW makes an expensive high-performance hybrid vehicle (i8) and a more moderately priced all electric vehicle (i3). If the sample contains mostly buyers of the i3, we would not expect vehicle performance to be a motivating factor.

Table 4
Multinomial results for vehicle choice.

Variables	(1) BMW	(2) Chevrolet	(3) FIAT	(4) Ford	(5) Nissan	(6) Tesla	(7) Toyota
Time trend	1.125***	0.915***	1.005	0.955***	0.928***	0.920***	0.914***
	(0.00887)	(0.00434)	(0.00516)	(0.00468)	(0.00443)	(0.00453)	(0.00447)
Bay area	1.061	0.842	0.783*	0.752**	1.084	0.990	1.005
	(0.257)	(0.109)	(0.110)	(0.0998)	(0.138)	(0.137)	(0.140)
Southern California	1.165	0.918	0.649***	0.648***	0.469***	0.786*	0.928
	(0.270)	(0.112)	(0.0856)	(0.0805)	(0.0568)	(0.103)	(0.122)
Male	1.137	1.049	0.657***	0.778***	0.913	1.209**	0.777***
	(0.157)	(0.0809)	(0.0552)	(0.0624)	(0.0707)	(0.0998)	(0.0633)
No answer (age)	0.746	0.865	0.341***	0.887	0.337***	3.989***	0.676
	(0.344)	(0.224)	(0.102)	(0.248)	(0.0882)	(1.086)	(0.183)
Age	0.999	1.000	0.988***	1.005*	0.983***	1.030***	0.994*
	(0.00534)	(0.00307)	(0.00334)	(0.00327)	(0.00301)	(0.00355)	(0.00326)
No answer (education)	3.458**	0.921	1.025	0.782	1.868**	1.091	1.138
	(1.718)	(0.287)	(0.361)	(0.262)	(0.586)	(0.350)	(0.373)
Refuse to answer (education)	0.843	0.949	0.714	0.836	1.441	1.082	1.728*
	(0.570)	(0.300)	(0.265)	(0.277)	(0.457)	(0.355)	(0.557)
College	1.705**	0.953	1.006	0.804*	1.336**	1.234*	1.300**
	(0.377)	(0.102)	(0.121)	(0.0898)	(0.152)	(0.151)	(0.156)
Graduate degree	1.620**	0.824*	0.836	0.668***	1.527***	1.161	1.322**
	(0.359)	(0.0895)	(0.102)	(0.0755)	(0.174)	(0.142)	(0.160)
No answer (income)	4.233**	1.525**	1.238	1.700**	0.930	8.634***	1.245
	(2.433)	(0.318)	(0.288)	(0.374)	(0.195)	(2.390)	(0.269)
Refuse to answer (income)	7.216***	1.309	1.057	1.466*	0.899	9.294***	0.953
	(3.948)	(0.254)	(0.229)	(0.302)	(0.173)	(2.470)	(0.193)
\$50,000–\$99,999	3.324**	1.294	1.181	1.286	0.975	1.160	0.875
	(1.799)	(0.228)	(0.226)	(0.241)	(0.171)	(0.311)	(0.161)
\$100,000–\$199,999	3.494**	1.418**	1.192	1.550**	0.949	2.798***	0.852
	(1.851)	(0.239)	(0.220)	(0.278)	(0.159)	(0.703)	(0.150)
\$200,000–\$299,999	6.943***	1.437**	1.127	1.732***	0.767	6.497***	0.833
	(3.751)	(0.264)	(0.229)	(0.338)	(0.141)	(1.695)	(0.161)
\$300,000–\$399,999	10.22***	1.634**	1.511*	1.680**	0.809	12.05***	0.907
	(5.808)	(0.373)	(0.378)	(0.408)	(0.185)	(3.512)	(0.220)
\$400,000–\$499,999	8.486***	1.239	0.987	1.166	0.537**	18.02***	0.416**
	(5.285)	(0.365)	(0.330)	(0.372)	(0.162)	(5.999)	(0.144)
More than \$500,000	11.96***	0.966	1.115	0.786	0.329***	33.96***	0.662
	(6.914)	(0.246)	(0.316)	(0.227)	(0.0907)	(10.17)	(0.180)

(continued on next page)

Table 4 (*continued*)

Variables	(1) BMW	(2) Chevrolet	(3) FIAT	(4) Ford	(5) Nissan	(6) Tesla	(7) Toyota
Constant	0.00202***	17.73***	4.190***	6.475***	38.81***	0.475**	17.61***
	(0.00131)	(4.947)	(1.263)	(1.902)	(10.78)	(0.165)	(5.157)
Observations	19,460	19,460	19,460	19,460	19,460	19,460	19,460

Robust standard errors in parentheses.
* $p<0.1$.
** $p<0.05$.
*** $p<0.01$.

6.2. Electric vehicle choice

We now use the CVRP data to study the relationship between buyer demographics and electric vehicle choice for the universe of survey respondents who purchased an electric vehicle between September 2012 and May 2015 and applied for a rebate. This relationship is estimated using the following multinomial logit model:

$$P(Y_i = j) = e^{\beta_j' x_i} / \sum_{k=0}^{J} e^{\beta_k' x_i}. \tag{1}$$

$P(Y_i = j)$ is the probability that consumer i chooses a vehicle from manufacturer j when presented with the set of manufacturers J. X_i is a vector of attributes describing the decision maker and contains demographic and geographic characteristics and a time trend.

Results from the multinomial logit model are presented in Table 4. All manufactures of plug in electric hybrid vehicles that were eligible for a rebate other than BMW, Chevrolet, FIAT, Ford, Nissan, Tesla, and Toyota are in the base category. For ease of interpretation, the coefficients are presented as relative risk ratios and can be compared to one. For the highest quality vehicles (BMW and Tesla) the probability of choosing one of these vehicles is increasing monotonically with income. These vehicles are also purchased more frequently by those with higher levels of education. This result suggests that the high quality, high-performance electric and hybrid vehicles on the market are not being purchased by the average vehicle buyer.

6.3. Testing for evidence of increased joint purchases of EVs and solar systems

We hypothesize that quality improvements and falling prices of both electric vehicles and solar panels will lead to households increasingly purchasing both durable goods as a bundle. If our hypothesis is correct, the correlation between the share of households with solar panels and electric vehicles will rise over time.[13] To test this claim, we run census tract/year level regressions using the California data and run Eq. (2):

$$Y_{it} = \beta Solar_{it}\, \lambda_t + \alpha X_i + \lambda_t + \varepsilon_{it}. \tag{2}$$

Y_{it} is the number of electric or electric-gas hybrid vehicles in census tract i in year t divided by the number of households in each census tract. $Solar_{it}$ is the percentage of households that have a solar PV system installed, and X_i is a vector of census tract demographics, county fixed effects and an intercept. λ_t are year fixed effects. We interact these year fixed effects with the percentage of households with solar to allow the correlation between solar PV systems and electric vehicles to vary over time. ε_{it} is the error term and standard errors are clustered at the county level.

The results from this specification are presented in Table 5. After controlling for census tract demographics, political ideology, and county-level unobservable, we find that the correlation between the share of households with solar and the share of households with an electric or hybrid vehicles is getting stronger and more positive over time. From 2010 through 2012, there was a negative and statistically significant correlation between these two variables. Beginning in 2013, the correlation between these two variables becomes positive and statistically significant. In 2013, 2014, and 2015, a one percentage point increase in share of households with solar is associated with a 0.0442, 0.0867, and 0.0872 percentage point increase in the share of households with solar, respectively. While these estimates appear to be small, a 0.0872 percentage point increase in the share of households with an electric or hybrid vehicles is equal to a 30% increase from the mean. The correlation between solar and electric vehicles turns positive the year after the Tesla Model S was released. These results are consistent with our hypothesis that consumers view these two durables goods as complements and that more consumers to bundle these two durable goods over time. While the results in Table 4 show a strong income effect for high-end electric and

[13] As a robustness check, the regressions were estimated using only census tracts that show up in the PG&E, SCE, and SDG&E utility areas. The results were qualitatively similar to the full sample of census tracts.

Table 5
Regression results for the percentage of electric and hybrid vehicles in a census tract.

Variables	(1) (%) Electric	(2) (%) Hybrid	(3) (%) Electric or hybrid
(%) Solar × 2010	−0.105***	−0.0446***	−0.150***
	(0.0254)	(0.0127)	(0.0378)
(%) Solar × 2011	−0.0593***	−0.0360***	−0.0954***
	(0.0159)	(0.0101)	(0.0257)
(%) Solar × 2012	−0.0287***	−0.00423	−0.0330**
	(0.00954)	(0.00668)	(0.0154)
(%) Solar × 2013	0.0177*	0.0245***	0.0422**
	(0.00889)	(0.00880)	(0.0171)
(%) Solar × 2014	0.0462***	0.0406***	0.0867***
	(0.0138)	(0.0125)	(0.0258)
(%) Solar × 2015	0.0506***	0.0366***	0.0872***
	(0.0161)	(0.0122)	(0.0278)
(%) Democrat, green, natural law, or peace and freedom	−0.000975	−0.00202	−0.00300
	(0.00148)	(0.00146)	(0.00291)
(%) Bachelor's degree or higher	0.00416***	0.00177***	0.00593***
	(0.000990)	(0.000529)	(0.00126)
Median income	0.00427***	0.00245***	0.00672***
	(0.00120)	(0.000424)	(0.00158)
(%) Black	0.00171	0.00121	0.00292
	(0.00115)	(0.000765)	(0.00185)
(%) Hispanic	0.00200**	0.000898	0.00290**
	(0.000765)	(0.000579)	(0.00128)
People per square mile	−2.64e−07	−8.03e−07	−1.07e−06
	(9.90e−07)	(7.88e−07)	(1.73e−06)
Miles to central business district	3.64e−05	6.32e−05	9.96e−05
	(0.000616)	(0.000362)	(0.000897)
Constant	−0.187	−0.0342	−0.221
	(0.165)	(0.0794)	(0.233)
Observations	47,802	47,802	47,802
R-squared	0.358	0.413	0.417
County fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes

Notes: The dependent variables in these regressions measure the number of each vehicle type in a census tract that applied for a rebate divided by the number of households in each census tract. The variable "% Solar" is the primary variable of interest and is equal to the number of solar installations in each Census tract divided by the number of households in each Census tract. The percentage of households with solar panels installed has been interacted with year specific dummy variables so that the correlation between solar panels and electric vehicles can vary over time.
Robust standard errors in parentheses.

* $p<0.1$.

** $p<0.05$.

*** $p<0.01$.

hybrid vehicles, the results in Table 5 show a significant correlation between solar panels and electric vehicles even after controlling for income, education, political ideology, and distance to a city center.

We recognize that these reduced form estimates do not provide information on what would be the correlation between these choices in situations where gas prices higher, electric vehicles were more or less expensive, or if electricity prices were higher or lower.

7. Emerging trends for electric vehicles and solar panels

Several promising trends suggest that the price of solar panels and electric vehicles will decline and that their quality will improve over time. In this section, we provide some evidence that the price of adopting these two technologies is falling at the same that time quality is improving.

7.1. New financing options reduce the likelihood of binding liquidity constraint

Dating back at least to Hausman (1979) economists have noted that consumers dislike making large upfront investments in more energy efficient durables even if these durables offer large future reductions in expected operating costs. Allcott and Wozny (2014) estimate that car buyers reveal an indifference between achieving a $1 reduction in the present value of energy savings versus not paying 76 cents more in purchasing the vehicle. Such a high implied discount rate suggests that any financing options that reduce the upfront out of pocket costs could lead to many marginal durables buyers to change their behavior. When state and federal tax incentives are considered, it is now possible for consumers to invest in these technologies with little to no upfront costs.[14]

Sellers of solar panels and EVs have increased the menu of financing options for paying for these products. One of the more innovative financing arrangements came through Tesla's resale value guarantee. This allowed consumers who buy a Tesla and finance their purchase through Tesla's official financing program to know exactly what Tesla is willing to pay for the vehicle after three years of ownership. The resale price was equal to 50% of the base price of the 60 kW h version plus 43% of the price of all options including the upgrade to the 85 kW h battery pack. A back-of-the-envelope calculation shows that this buy back value was sufficient to pay off the remaining loan balance if the buyer no longer wants to continue making the payments to Tesla after three years.

Consumers who are considering installing solar panels on their home also have a variety of financing options from which they can choose. For households with low incomes that simply want to take advantage of "green electricity" there are solar power purchase agreements that allow them to do this with no out-of-pocket costs. The solar company owns and maintains the equipment and the household simply pays the solar company for the electricity that is generated. While the electricity rates under this arrangement will be less than those charged by most utility companies, this option does not give the ability to lock into a long term low electricity rate that is available if the solar system is leased or purchased.

For households with higher incomes and a qualifying credit score, it is now possible to lease or purchase solar panels with $0 upfront cost. Since the solar companies install the system and take responsibility for all of the maintenance at no cost to the homeowner, the decision to lease or purchase depends on the financial characteristics and goals of the household. Before the option to purchase a solar system for $0 money down, many homeowners made the decision to lease a system to reduce their out of pocket costs. This new option allows consumers to own their system from day one and allows them to receive the federal tax credit that is equal to 30% of the cost of the solar system. For households choose to lease their solar system, the 30% federal tax credit goes to the solar company to offset the upfront cost of the system.[15]

Solar city (the corporation that Tesla is now in the process of merging with) has a financing arrangement that allows qualified consumers to purchase their solar system with monthly payments determined by the amount of energy produced by the solar panels. This option allows a household to: (1) own their system from day one with no upfront costs, (2) receive all of the state and federal tax benefits, (3) have no responsibilities for the solar system's maintenance, and (4) not be locked in to a monthly payment in the event the system does not produce enough electricity. Lastly, in the event that the homeowners decide to sell their home, the solar system is now considered an asset (compared to a liability with the lease agreement) that will make the home more attractive to potential buyers.

These new financing arraignments will lead some households at the margin to adopt solar panels and electric vehicles to take advantage of significant reductions in there operating expenses even if the environmental benefits are not their primary

[14] State and federal tax incentives now allow consumers to purchase or lease these vehicles for $0 down. Since the tax credit can be claimed by the manufacture and applied to the down payment, consumers do not have to make this expenditure out of pocket and wait until they file their taxes to be reimbursed. Since this does not apply to non-plug in vehicles, these incentives can lead the marginal consumer to make the switch to a plug-in hybrid or EV. Since the rebates are also available to consumers who lease a plug-in hybrid or all-electric vehicle, it is possible for a skeptical consumer to experience this type of vehicle with a low monthly payment and without being locked in to a more expensive long-term loan payment.

[15] If the household's tax liability is less than 30% of the cost of the system, or if the household has $0 tax liability, they will have to pay these upfront costs out of pocket.

motivation. However, for households that drive only a few miles per month, or have lower than average electricity costs, or are in areas with lower gas prices, it may not be in their best interest to purchase these durable goods.

8. Conclusion

In the absence of carbon pricing, a typical suburban Californian household who drives 15,000 miles per year and whose daily consumption of electricity is 25 kW h has an annual carbon footprint of 8.2 t from transportation and household electricity consumption.[16] If the social cost of a ton of carbon dioxide is $35, this translates into a suburban household social cost of $288 per year. Such households are both contributing to the challenge of climate change and are more likely to oppose carbon pricing (because they would pay more) than center city residents with a smaller carbon footprint.

This study has investigated a nascent promising trend that suburban households will be increasingly likely to purchase both solar panels and electric vehicles. Using California data, we have documented using both individual level survey data and detailed tract level geography data that there is evidence that consumers view electric vehicles and solar panels as complements. After controlling for census tract demographics including income, education, political ideology, and county-level unobservables, our results show that areas in California with higher levels of solar panels also have higher levels of all electric and plug-in hybrid vehicles and that this correlation is getting stronger over time. Results from a survey of electric vehicle owners show that many owners of electric or hybrid vehicles have solar panels installed or plan to have them installed within one year. Interestingly, those that purchased an all-electric vehicle were more likely to have or plan to have solar panels installed. Since owners of all electric vehicles do not have to rely on gasoline as a fuel source, having solar panels installed makes it possible for households to reduce significantly their operating expenses from household and transportation activities.

We argue that the joint purchase of electric vehicles and solar panels is one way to reduce significantly carbon emissions in the suburban United States. Because electric vehicles may lead to more environmental damages than a comparable conventional vehicle in the majority of the United States (Graff Zivin et al., 2014; Holland et al., 2015), growth in electric vehicles alone could lead to more, not less, greenhouse gas emissions in these areas. Households that invest in both solar panels and electric vehicle, and size their solar system to offset the additional electricity used by their vehicle, can eliminate their carbon footprint from household and transportation activities.

Past and current growth in solar panels and electric vehicles has been dependent on significant state and federal subsidies. With the election of Donald Trump as President of the United States, an interesting natural experiment will now play out as federal subsidies for such green technologies are likely to fade away. In the absence of these subsidies, we argue that quality improvements, price reductions, and innovative financing provide a promising future for the joint demand in these durable goods. Holding quality constant, as the cost of operating an electric vehicle drops relative to that of a conventional vehicle, households will be more likely to choose the more environmentally friendly EV. If a sufficient number of suburbanites made this "green choice," then the suburban carbon curve would bend such that the differential in carbon production between center city residents and suburban residents would shrink. Given that a majority of the U.S population lives in the suburbs, such a decline in suburban emissions could help nudge the U.S median voter towards supporting carbon pricing.

Appendix

See Table A1 here.

[16] We are assuming that the vehicle achieves 27.5 MPG and that the power plant's emissions factor is the same as California's. See the EPA's eGRID 9th edition summary tables for more information on state-level emissions factors.

Table A1
Description of datasets.

Data	Description	Source	Unit
Micro data			
Vehicle rebates	• Individual level data for California residents that applied for a rebate through the California Clean Vehicle Rebate Project • Date of application • Vehicle make and type • Census tract and zip code identifiers	California's Clean Vehicle Rebate Project: Rebate Statistics	Applicant
Vehicle Rebate Survey	• Motivations for purchase • Vehicle make and type • No geographic identifier	California's Clean Vehicle Rebate Project: Survey Dashboard	Applicant
Solar	• All interconnected solar PV systems within PG&E, SCE, and SDG&E. • Zip code identifier	California's Distributed Generation statistics	Applicant
Aggregated Data			
Political	• Number of registered voters by political party in 2010	Statewide Database-University of California, Berkeley.	Census Block
Demographics	• Census tract characteristics	2014 American Community Survey 5-year Estimates	Census Tract

Notes: This table provides a brief description of all the data sets that were used in the analysis. Census block data were aggregated to the Census tract by summing the totals for each Census block in each Census tract. Zip code data were matched to Census tracts using the United States Department of Housing and Urban Development's USPS to Zip Code crosswalk files.

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